Multiscale Deterministic Wave Modeling with Wind Input and Wave Breaking Dissipation

Lian Shen
Department of Civil Engineering
Johns Hopkins University
Baltimore, MD 21218
phone: (410) 516-5033 fax: (410) 516-7473 email: LianShen@jhu.edu

Award Number: N00014-06-1-0658

LONG-TERM GOAL

The primary focus of this research is to use large-eddy simulation (LES) and large-wave simulation (LWS) to obtain improved physical understanding of wind-wave-ocean interactions, based on which we aim to develop effective models of wind input and whitecapping dissipation for phase-resolving, nonlinear wave-field simulation at large scales. Our ultimate goal is to establish a numerical capability for predicting deterministically large-scale nonlinear wave-field in real marine environments with the presence of significant wind and wave breaking effects.

OBJECTIVES

The scientific and technical objectives of this research are to:

- develop advanced LES and LWS numerical capabilities for wind-wave-ocean interactions with physics-based subgrid-scale (SGS) models; use high-performance LES/LWS as a powerful research tool to obtain an improved understanding of the flow structure in the atmosphere-ocean wave boundary layer
- develop effective models for wind input and the associated whitecapping dissipation in a direct phase-resolving context, which can be readily incorporated into the deterministic numerical tool of the Simulation of Nonlinear Ocean Wave-field (SNOW)
- understand effects of multi-scale physics and environmental uncertainties upon wave deterministic propagation, and to effectively model these effects; validate the direct modeling and simulation approach, and perform direct comparison with existing theories and field measurements

APPROACH

We use a systematic, multiscale approach to investigate and to model effects of wind input and whitecapping dissipation on wave-field evolution. This includes: (1) use LES and LWS to obtain improved physical understanding of wind-wave-ocean interactions at small scales (O(1~10) significant gravity wave lengths); (2) based on the LES/LWS results, develop advanced wind input and whitecapping models in a direct physical context in terms of surface pressure distribution and flow field filtering, respectively; and (3) incorporate the models into SNOW simulation to investigate local effects of wind forcing and whitecapping on large-scale wave-field evolution. Because the physics are

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **30 SEP 2008**	2. REPORT TYPE **Annual**	3. DATES COVERED **00-00-2008 to 00-00-2008**

4. TITLE AND SUBTITLE **Multiscale Deterministic Wave Modeling With Wind Input And Wave Breaking Dissipation**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Johns Hopkins University,Department of Civil Engineering,Baltimore,MD,21218**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
code 1 only

14. ABSTRACT
The primary focus of this research is to use large-eddy simulation (LES) and large-wave simulation (LWS) to obtain improved physical understanding of wind-wave-ocean interactions, based on which we aim to develop effective models of wind input and whitecapping dissipation for phase-resolving, nonlinear wave-field simulation at large scales. Our ultimate goal is to establish a numerical capability for predicting deterministically large-scale nonlinear wave-field in real marine environments with the presence of significant wind and wave breaking effects.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**7**	

being investigated and modeled in a direct, phase-resolving context, we expect that the models developed in this study are more likely to succeed than traditional phase-averaged parameterizations.

The numerical study of wind-ocean-wave interactions are at two fronts: viscous flow simulation for turbulence-wave interactions at small scales, and potential flow based wave simulation at large scales. For viscous air-wave-water simulations, we use the approach of large-eddy simulation based on filtered Navier-Stokes equations, in which large turbulence eddies are computed explicitly with effects of small eddies being represented by SGS models. A similar LWS approach is used for wave-turbulence interactions, with large wave components being simulated directly and small wave effects modeled.

One of the major issues with simulating coupled air-wave-water turbulent flows is the presence of a deformable, time-evolving free surface, which makes the air and water computational domains irregular. The location and geometry of the free surface are unknown beforehand, and they are part of the solution to be solved for. To overcome this difficulty, we have developed a suite of complementary computational methods, which include a boundary interface tracking method based on boundary-fitted grids for moderate wave slope and an Eulerian interface capturing method based on a level set approach for steep/breaking waves.

The wind input and whitecapping models developed from LES/LWS study will be incorporated to potential flow wave computation using SNOW developed at MIT. The SNOW uses a high-order spectral (HOS) method, which is a pseudo-spectral method developed based on the Zakharov equation and mode-coupling idea. The wind input to the wave-field is modeled by surface distribution of pressure, while wave breaking dissipation is represented by advanced filtering treatment in physical and spectral spaces.

The multiscale modeling of ocean wave-fields will be one of the foci of this research. At local scales, we apply LES and LWS, with which the large eddies and waves are resolved explicitly and structures smaller than the computational grid are modeled. The wind input and models developed based on local-scale LES/LWS are then implemented in SNOW for large-scale simulations. In SNOW, the nonlinear wave interactions, the wind input, and the whitecapping dissipation are all represented in a direct physical context. This approach provides a powerful tool and a unique opportunity to investigate the effects of local processes on large-scale wave-field evolution in a physical-based, deterministic way.

Large-scale high-performance computation on parallel computers is used to meet the computational challenges in the turbulence and wave simulations. Massage passing interface (MPI) based on domain decomposition is used for parallelization.

WORK COMPLETED

During the fiscal year of 2008, substantial progresses have been made, which include:

- We have developed a numerical capability for the truly coupled simulation of wind and waves. The fully nonlinear evolution of irregular, broadband wavefield is captured faithfully in our simulation. Dynamic two-way coupling between wind and wave fields are achieved.

- We have investigated the dynamic nonlinear evolution of phase-resolved, developing sea under winds. Difference between two-way and one-way wind-wave coupling has been elucidated.
- We have elucidated effect of surface drift through mechanistic study.
- We have elucidated and quantified effect of wave nonlinearity.
- Through mechanistic study, we have obtained substantial physics insights to the wind-wave coupling dynamics in terms of: mean and instantaneous velocity fields, flow separations, coherent vortical structures, Reynolds stress and momentum transport, turbulent kinetic energy budget, and enstrophy balance.
- We have elucidated and quantified wind input for the dynamic evolution of waves.
- We have simulated steep and breaking waves as well as the interaction processes between waves and ocean turbulence.

RESULTS

In this study we have developed a numerical capability for the phase-resolving direct simulation of dynamically evolving nonlinear waves under winds. To have the two-way dynamic coupling of wind and wave interaction, at each time step, wind simulation feeds the high-resolution wind pressure result to wave simulation as wind input to obtain wind-wave growth, while wave simulation provides precise sea surface geometry and velocity directly as boundary conditions for wind simulation.

Using this advanced numerical tool, we have successfully simulated dynamically evolving broadband irregular wavefield under winds. Figure 1 shows results of wind speed, ocean wave profile, and distribution of wind pressure at sea surface. For comparison, a simulation with wind-to-wave one-way coupling is also performed. It is found that the dynamic two-way coupling results in qualitative difference in the subsequent phase-resolved surface wavefield as seen for the two cases starting from identical (SNOW-provided JONSWAP) waves. The two-way coupled simulation predicts higher near surface wind kinetic energy, more grouping of steep waves, and increased surface pressure intermittency. The qualitative difference in the phased-resolved wavefield is however manifested only weakly in phase-averaged results such as the the wave spectra shown in Figure 2.

Results in Figures 1 and 2 show the importance of wave nonlinearity and two-way wind-wave coupling in the phase-resolving wavefield prediction for naval applications. To understand the underlying dynamics, we have performed a detailed mechanistic investigation. Figures 3, 4, and 5 show representative results on wind pressure input to wave, coherent vertical structures, and Reynolds stress associated with the vertical momentum transport, respectively.

Figure 3 plots the phase-averaged wave-correlated pressure contours of winds. It is shown that, for the young wave case ($c/u_* = 2$), the pressure contours are tilted at a short distance above the wave. For the mature wave case ($c/u_* = 25$), the high pressure does not extend to the bulk flow much comparing to the wave amplitude. The qualitative difference between using linear versus nonlinear surface waves is noteworthy. Pressure profiles over nonlinear waves show greater forward/backward and crest/trough asymmetries. Estimates of wave growth parameter based on this show appreciable quantitative differences depending on wave age.

In Figure 4 we plot the coherent vortices in the wind turbulence. It is found that wind field near surface waves is characterized by inclined quasi-streamwise and horseshoe vortices, of which the occurrence is wave phase dependent. Wave nonlinearity changes the spatial distribution of vortices, which may in turn affects the pressure distribution for wind input to wave and vertical momentum transport.

In the case of turbulence over water waves, the distribution of Reynolds stress is found to be substantially different from flat wall case. Figure 5 shows contours of Reynolds stress for the $c/u^*=2$ case. It is apparent that the Reynolds stress strongly depends on wave phase. The maximum of Reynolds stress lies above wave trough. There is another high Reynolds stress region extending from the maximum location to downstream direction and is lifted up above wave crest. Again, wave nonlinearity makes the distribution of Reynolds stress more asymmetric with respect to wave profile. At this small wave age, Reynolds stress above nonlinear wave is larger than that above linear wave, and the high-value region is located closer to the wave surface.

IMPACT/APPLICATION

This project aims at a basic scientific understanding of the air-sea-wave interaction physics and numerical capability development for ocean wave-field prediction pertinent to Navy applications. It addresses a critical need of the Navy to bridge the gap between the modeling of small-scale air-sea-wave interaction physics and the prediction of ocean waves at regional scales. The proposed research will provide the Navy with a new powerful tool to predict deterministically nonlinear, large wavefield with finely-resolved temporal and spatial details. The new phase-resolved, deterministic tool is fundamentally distinct from existing phase-averaged, statistical wave modeling tools such as WAM and SWAN, with the potential of being able to make more accurate prediction because of its direct, physics-based approach. Furthermore, the results of this work will also be useful for the comparison and calibration of field measurements and for obtaining physical insights to improve existing phase-averaged wave prediction models.

RELATED PROJECTS

This work complements a number of on-going ONR projects. In particular, it is closely related to the development of Simulation of Nonlinear Ocean Wave-field (SNOW) by Professor Dick Yue’s research group at MIT. The wind input and wave breaking dissipation modeling in this project is to be incorporated into SNOW, and together we will improve the SNOW capability for it to become a next generation of wave model capable of predicting nonlinear wave evolution subject to winds and whitecapping. Such numerical tools will be useful for high-resolution wave-field study.

HONORS/AWARDS/PRIZES

T.Y. Ogilvie Young Investigator Lectureship
Invited to be a keynote speaker at the 2nd International Conference on Turbulence and Interaction

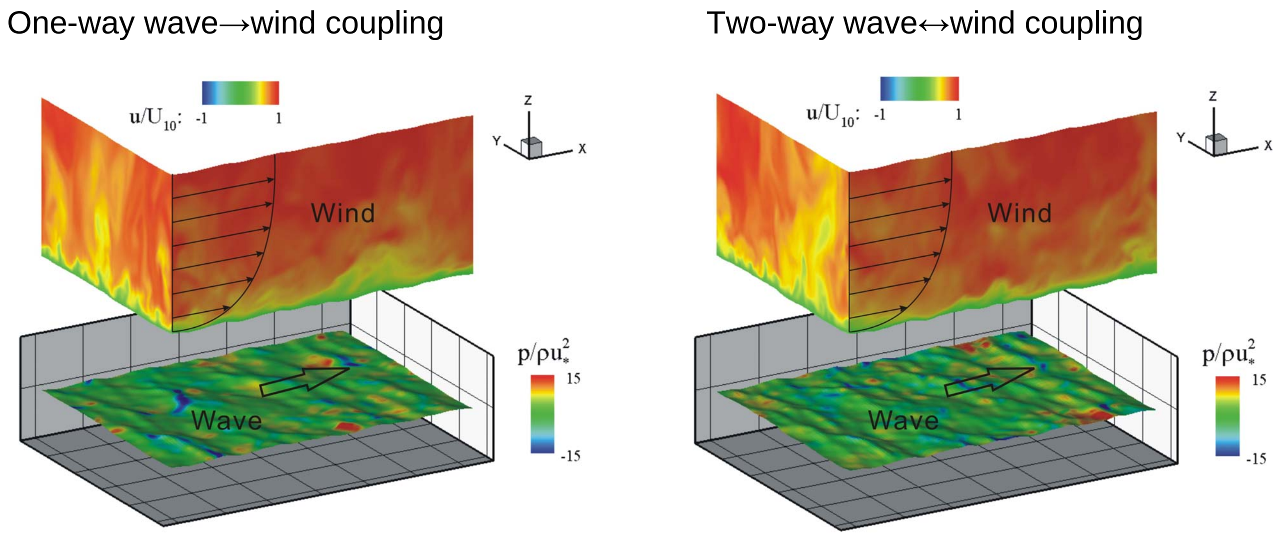

Figure 1. Instantaneous wind field over dynamically evolving wave field. Plotted are wind speed, ocean wave profiles, and distribution of wind pressure at sea surface. Left: simulation with one-way wave-to-wind coupling; right: simulation with two-way wind-wave coupling. The ocean wave fields start from identical JONSWAP spectra for the two cases.

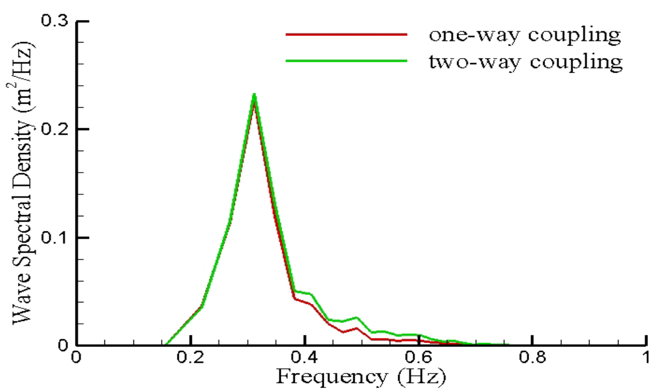

Figure 2. Frequency spectra of ocean waves obtained from wind-wave coupled simulation.

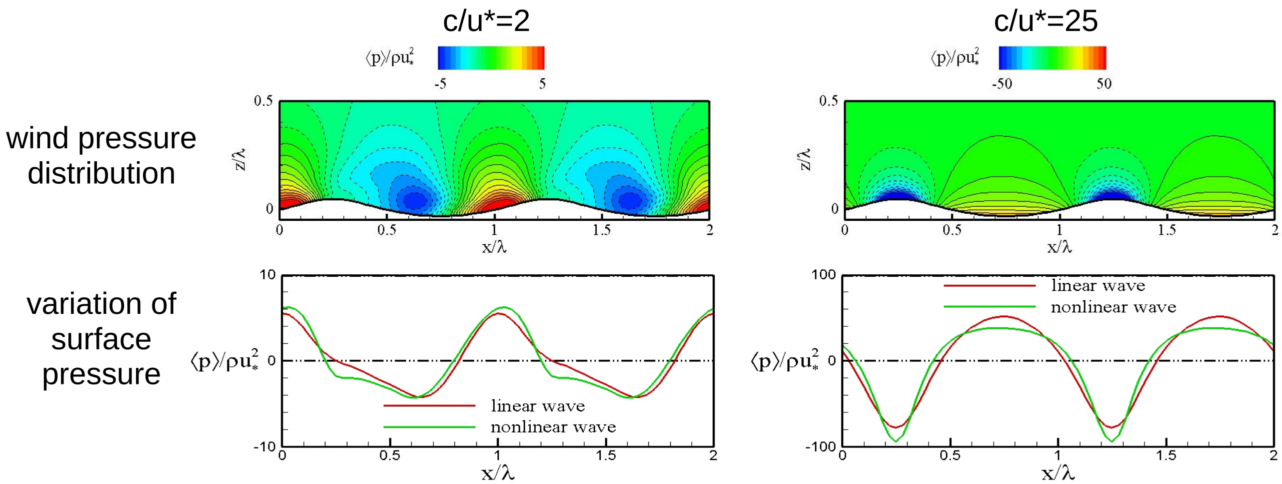

Figure 3. Upper figures: distribution of pressure in the wind field for young/slow waves of $c/u_* = 2$ (left) and fast/mature waves of $c/u_* = 25$ (right). The results are phase-averaged with respect to water waves. Bottom figures: corresponding pressure distribution along the wave surface with comparison between linear and nonlinear waves. In the upper figures, nonlinear wave results are shown.

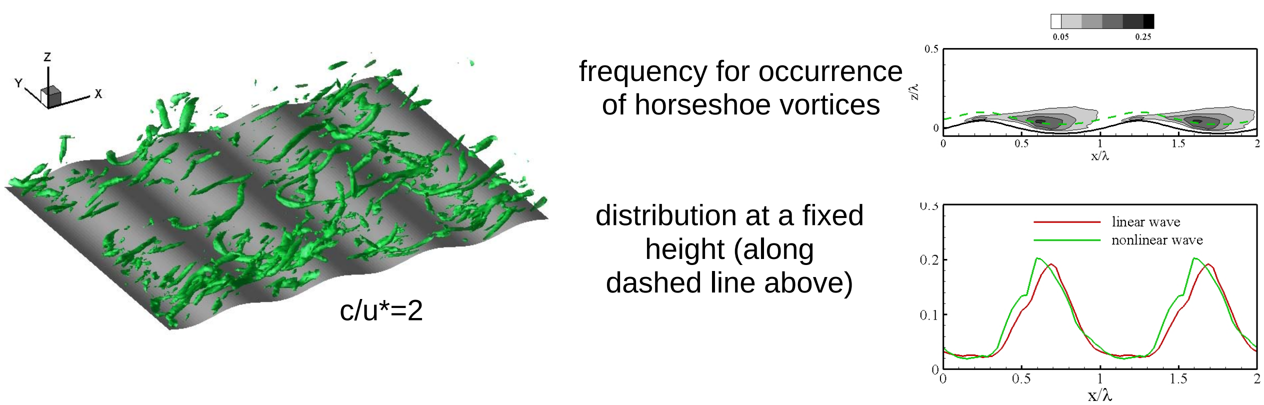

Figure 4. Left: coherent vortex structures in wind field over waves. The wind is blowing in the wave propagation direction. The vortices are represented by isosurfaces of second largest eigenvalue of the tensor $\mathbf{S}^2 + \mathbf{\Omega}^2$, with $\mathbf{S}$ and $\mathbf{\Omega}$ respectively the symmetric and anti-symmetric parts of the velocity gradient tensor $\nabla \vec{u}$. It is shown that quasi-streamwise and horseshoe vortices are the characteristic vortical structures. Right: relative frequency of the occurrence of horseshoe vortices phase-averaged with respect to waves (top), and the comparison between linear and nonlinear wave cases (bottom).

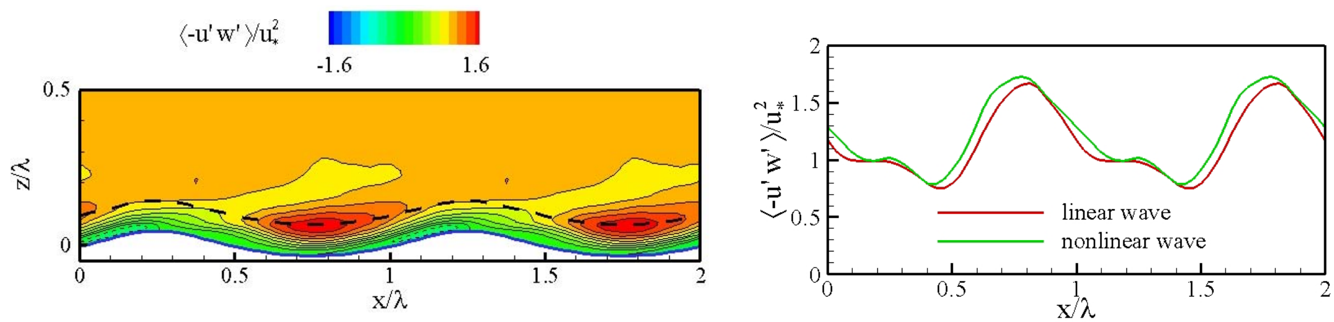

Figure 5. Left: distribution of Reynolds stress in the wind field. The results are phase-averaged with respect to water wave. The young wave case $c/u_* = 2$ is shown here. Right: comparison between linear and nonlinear wave cases of the Reynolds stress at the fixed height marked by the dashed line in the left figure.